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Indicators of environmental performance to assess wood-based bioenergy production: A case study in Northern Italy

Elvira Buonocore [a], Alessandro Paletto [b], Giovanni F. Russo [a], Pier Paolo Franzese [a, *]

[a] Laboratory of Ecodynamics and Sustainable Development, Department of Science and Technology, Parthenope University of Naples, Italy
[b] Council for Agricultural Research and Economics - Forest Monitoring and Planning Research Unit (CREA-MPF), Villazzano, Trento, Italy

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A B S T R A C T

Increased environmental concerns, mainly related to fossil fuels consumption and global climate change, have drawn the attention to the dependence of human society on energy supply. As a consequence of EU Directives setting mandatory renewable energy targets up to 2020, member states are boosting renewable energy and bioenergy production. The use of wood biomass for bioenergy production can entail important benefits, including improved energy security due to a smaller dependence on fossil fuel supply, mitigation of climate impact, and revitalization of rural economies connected to new job opportunities. Nevertheless, bioenergy production also involves environmental and socio-economic concerns. The environmental, economic, and social sustainability of bioenergy production needs to be assessed through a set of multicriteria indicators. In this study, Life Cycle Assessment (LCA) was used to explore the environmental performance of bioenergy production in an Alpine area of Northern Italy. In particular, the environmental impacts of a wood-based bioenergy plant utilizing local residues from wood industries and forestry operations were investigated. The amount of CO_2-eq emissions (0.25 kg CO_2-eq kWh^{-1}) and the fossil demand (0.09 kg oil-eq kWh^{-1}) calculated for the investigated bioenergy plant resulted lower than the values characterizing fossil fuels-based power plants. Yet, the environmental performance of the investigated bioenergy plant was affected by the consumption of methane, still used in the plant to cover peak loads. The results showed that the use of local wood biomass in the investigated Alpine area is a desirable option for recycling wood residues while supporting heat and electricity production. The findings of this study can support local managers and policy makers committed to plan and implement renewable energy strategies and circular economy patterns. In addition, they can be useful to assess the potential upscale of this bioenergy option at regional and national level considering the availability of wood residues (from forestry and industrial sector) while verifying possible operational constraints at larger scales. Future studies could also integrate environmental accounting with other assessment methods exploring the economic profitability and social desirability of wood-based bioenergy production in mountain areas characterized by low population density and large forest cover.

1. Introduction

1.1. Scientific background

Increased environmental concerns, mainly related to global climate change and oil price increase, have drawn global attention to the dependence of society on energy supply. In 2009, the EU Directive 2009/28/EC set mandatory renewable energy targets for member states, requiring at least 20% of EU total energy needs to be replaced by 2020 with renewable energy sources, and at least 10% of transport fuels to be replaced by biofuels (European Commission, 2009). In 2016, due to many environmental concerns, socio-political changes, and new perspectives on sustainability, the European Commission published an update of the EU Directive 2009/28/EC, proposing the target of at least 27% share of renewable energy by 2030 and new sustainability criteria for bioenergy production (Zabaniotou, 2018).

In this context, European countries have responded to these energy and environmental challenges by boosting renewable

* Corresponding author.
E-mail address: pierpaolo.franzese@uniparthenope.it (P.P. Franzese).

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energy and bioenergy production (Gan and Smith, 2011; Lorenzi and Baptista, 2018; Marques et al., 2018).

Currently, biomass and waste are a significant global energy source, accounting for over 70% of all renewable energy production and providing a contribution to final energy consumption comparable to that of coal (IEA, 2017). Bioenergy consumption is large in the heat sector, although bioenergy for electricity and transport biofuels are growing faster, mainly due to higher levels of policy support in terms of new regulations and economic incentives. Globally, bioenergy accounts for 70% of the total renewable energy use for heat, 4% of renewable power capacity, and 4% of road transport fuel (IEA, 2017).

Bioenergy systems are expected to expand in coming decades for several reasons. Indeed, the use of biomass for energy production has the potential to deliver important benefits, such as improved energy security due to a smaller dependence on fossil fuel supply, reduction of greenhouse gas emissions and related climate impact, and revitalization of rural economies connected to new job opportunities (McBride et al., 2011).

Nevertheless, bioenergy production also involves environmental and socio-economic issues. The sustainability of bioenergy production is affected by environmental, economic, and social aspects (Jin and Sutherland, 2018). These aspects can be investigated through a multicriteria set of indicators supporting policy-makers and other stakeholders in the development of national bioenergy policies responding to environmental, social, and economic implications of bioenergy production and use (Franzese et al., 2014, 2019; GBEP, 2011; Häyhä et al., 2011; Myllyviita et al., 2013; Russo et al., 2014; Nikodinoska et al., 2018; Zabaniotou, 2018).

Several studies explored different aspects related to the environmental sustainability of biomass use for bioenergy production, including GHG emissions, energy and resource efficiency, land use, water use, and biodiversity protection (Mathioudakis et al., 2017; Pedroli et al., 2013; Saha and Eckelman, 2018; Welfle et al., 2017).

The economic sustainability of bioenergy involves short and long-term profitability of feedstock, interaction with technical advances in society, cost of installation and production, cost of feedstock transport, and the net balance between costs and benefits (Dale et al., 2013; Zabaniotou, 2018).

The social sustainability of bioenergy includes several aspects, such as preserving livelihoods and safe working conditions, ensuring affordable access to food, and guaranteeing the reliability of energy supply. Another relevant aspect is the need for open and transparent participatory processes engaging different stakeholders and local long-term sustainability plans (Dale et al., 2013; Vaidya and Mayer, 2016).

Ligno-cellulosic biomass is a suitable source for bioenergy production, especially when dealing with wood residues and waste. Several studies explored the environmental performance and sustainability of wood-based bioenergy chains showing that fuels and electricity from ligno-cellulosic biomass are likely to provide an environmentally sound bioenergy option (Buonocore et al., 2012, 2014; Franzese et al., 2009; González-García et al., 2014; Nikodinoska et al., 2017; Röder and Thornley, 2018; Ulgiati et al., 2010, 2011).

Forest ecosystems provide a large variety of ecosystem goods and services, among which the provision of wood biomass (Buonocore et al., 2018b; Häyhä and Franzese, 2014; Häyhä et al., 2015; Pauna et al., 2018). Nevertheless, there are several ecological concerns about the use of wood biomass for bioenergy production, including soil quality and biodiversity loss (Franzese et al., 2018a,b).

The removal of wood residues from forest ecosystems for bioenergy production may lead to the depletion of soil organic matter. In addition, nitrogen and other elements are abundant in twigs, foliage, and other residues. Therefore, the export of wood biomass from forests can remove a large amount of nutrients from soil (Pedroli et al., 2013).

Biodiversity conservation is a key issue in forest management. Sustainable forest management practices should be aimed at protecting critical habitats while monitoring the vegetation structure and growth stages of forest ecosystems over time (Kovac et al., 2018). The use of wood residues deriving from forestry can negatively affect biodiversity through the loss of dead wood and the removal of stumps, roots, and other logging residues. This loss can reduce soil flora and fauna species diversity. In addition, the increased use of fertilizers can have negative impacts on forest vegetation (Johansson et al., 2015; Naumov et al., 2018).

The development of wood-based bioenergy markets can generate many socio-economic benefits, including the creation of markets for wood biomass waste, the improvement of the economic viability of thinning and harvesting operations, the promotion of new crops to farmers, especially on marginal or unused land, and the creation of new employment opportunities in the whole bioenergy production chain (i.e., in the forestry, logistics, and conversion sectors) (Cambero and Sowlati, 2016; Hall, 2002; Nikodinoska et al., 2017; Peura and Hyttinen, 2011).

In the last decade, Life Cycle Assessment (LCA) has been widely used as a tool to evaluate the environmental performance of different renewable energy pathways (Buonocore et al., 2015, 2018a; Fazio and Monti, 2011; González-García et al., 2012; Raugei and Frankl, 2012; Röder and Thornley, 2018; Sastre et al., 2016).

Several LCA studies showed the benefits associated to bioenergy production in terms of greenhouse gas emissions reduction and energy balance (Muench and Guenther, 2013; Patel et al., 2016; Roos and Ahlgren, 2018). Recent studies used LCA to evaluate the potential in terms of climate change mitigation and fossil fuels savings when replacing fossil fuels-based electricity with wood-based electricity (Röder et al., 2019; González-García and Bacenetti, 2019).

1.2. Goal and motivation of the study

In this study, LCA was used to investigate the environmental impacts of a bioenergy plant powered by wood residues from sawmills and forestry to generate heat and electricity in the municipality of Cavalese (Northern Italy). Then, the environmental performance of the investigated plant was compared with other similar technologies based on the consumption of renewable and non-renewable resources.

This study follows a previous study by Buonocore et al. (2014) in which the forestry and logistics sectors of the same area were explored thus completing the investigation of the whole bioenergy value chain.

Previous studies investigated the environmental impacts due to wood energy production in alpine conditions. Among them, Valente et al. (2011) investigated bioenergy production in the study area by mainly focusing on global warming potential and socio-economic aspects. In the present study, several environmental impact categories (i.e., climate change, fossil depletion, freshwater ecotoxicity, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial acidification, and water depletion) were assessed to investigate the environmental impact of wood-based bioenergy production. In addition, the LCA indicators calculated for the investigated bioenergy plant were compared to those characterizing fossil-based technologies to assess the potential environmental benefits achieved when replacing fossil fuels with wood biomass for heat and electricity production.

2. Materials and methods

2.1. The LCA framework

LCA is a tool for assessing the environmental impacts of a product throughout its lifecycle, from raw material acquisition, via production and use phases, to waste management, from the so-called “cradle-to-grave” perspective (ISO 14040, 2006; ILCD, 2010). All human activities and processes result in environmental costs and impacts due to resource consumption and release of emissions into the environmental matrices. LCA allows for the identification and quantification of all energy, materials and emissions flows related to all steps involved in the life cycle of a product, assessing their environmental burden and evaluating opportunities for improvement.

Although the LCA tool is continuously under development, the International Standards of the ISO 14000 series provide a consensus framework for standardized LCA applications (ISO 14040-14044, 2006). In addition, the ILCD Handbook (ILCD, 2010) confirms the importance and the role of LCA as a decision-supporting tool in different contexts and at different scales, from product development to policy making. According to the ISO standards and the ILCD Handbook, LCA consists of four phases: Goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation.

2.2. Scope definition

2.2.1. The study area and the bioenergy plant

The bioenergy plant “Bioenergiafiemme” is located in the municipality of Cavalese (Northern Italy) and is mainly powered by wood chips from local wood industry and forestry. In particular, wood biomass is mainly derived from two Valleys, named “Fiemme” and “Fassa”, located in the northeastern part of the Province of Trento and embracing a productive forest area of 40,000 ha (Buonocore et al., 2014).

In these two valleys, as in the whole Province of Trento, all forestry activities take place according to forest management plans aimed at ensuring the sustainable exploitation of local forest ecosystems. These management plans entail actions needed to improve forest structure and growth and recommend selective cutting practices allowing the remaining forest to naturally regenerate overtime. The balance between wood biomass increment and felling ensures the sustainability of timber production over time. Moreover, the local forestry management plans set specific limits in terms of wood biomass removal after forestry operations. In fact, in the Fiemme and Fassa Valleys, 57% of the total amount of branches, bark, and tree tops generated by forestry is converted into wood chips for bioenergy production, while the remaining fraction (43%) is left on the soil (Nikodinoska et al., 2017). This practice ensures organic matter turnover, nutrient cycling, and biodiversity conservation in forest soils. Moreover, the use of herbicides and fertilizers is not allowed in the Fiemme and Fassa Valleys. This type of management plans reduces the possible environmental impacts of bioenergy production while favoring the long-term sustainability of wood biomass use as well as the health and integrity of forest ecosystems.

The bioenergy plant was initially equipped with two boilers powered by wood biomass and two emergency boilers powered by methane used to cover peak loads. The plant was built to feed a district heating network. Afterwards, new equipment and several modifications to the plant were implemented to increase the bioenergy production. In particular, an additional wood biomass boiler connected to an Organic Rankine Cycle (ORC) module was added for increasing heat and electricity generation.

The wood biomass used for bioenergy production is mainly derived from sawmills and other local wood industries (90%), while only a small percentage (10%) of the total used biomass is derived from forestry operations. The biomass is transported by trucks for an average distance of about 20 km. Trucks are unloaded at the plant where biomass is stored before combustion. The annual bioenergy generation consists of 31 GWh of heat and 11 GWh of electricity. The flowchart in Fig. 1 shows the main components of the investigated wood-based power plant, their interconnections, and the main input and output flows.

2.2.2. Functional unit, system boundaries, and basic assumptions

Basic choices and assumptions can greatly affect the results of LCA. Therefore, they need to be clearly stated when implementing a LCA study. In this study, the environmental impacts of the bioenergy plant were analyzed with reference to the functional unit (FU) of 1 kWh of delivered exergy. This choice was made according to the ILCD Handbook (2010), suggesting that different energy outputs can be consistently compared and summed by converting them into their exergy content.

The following equation was used to convert heat and electricity output flows into delivered exergy:

$$\text{Delivered exergy } (kWh_{exergy}) = \text{Delivered electricity } (kWh_{el}) + \text{Delivered heat } (kWh_{th}) \cdot \varsigma_{th}$$

ς_{th} is the Carnot factor calculated as 1- (Ta/Td), where Ta is the ambient temperature and Td the temperature of delivered heat (293 K and 368 K, respectively).

In this study, a “cradle to gate” LCA was performed. The boundaries were set as the physical system boundaries of the investigated power plant, thus including the construction of the plant and its operation. According to the literature, a life-span of 20 years was assumed for the power plant. Background processes (e.g., production of furnace and co-generation units) were included by using case studies from the *Ecoinvent* database (www.ecoinvent.org). The transportation of local wood-biomass to the plant was also accounted for, assuming an average transportation distance of 20 km. The decommissioning of the plant and the disposal of waste were not considered in this study.

The ReCiPe midpoint method was chosen among the LCA methods (www.rivm.nl/en/Topics/L/Life_Cycle_Assessment_LCA/ReCiPe). The method allowed for the assessment of the contribution of the investigated bioenergy plant to selected impact categories: climate change (GWP), fossil depletion (FD), freshwater

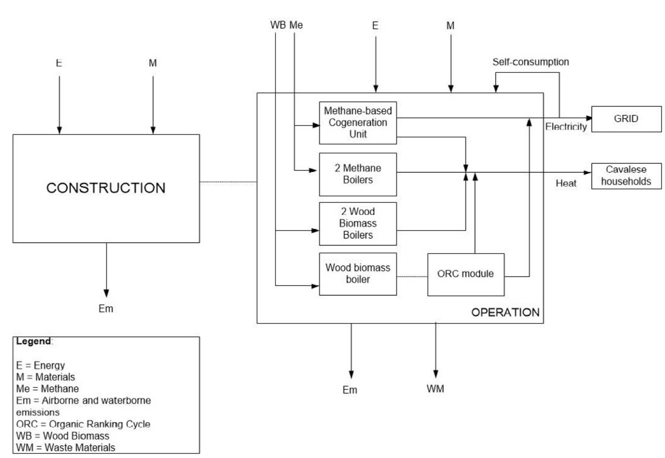

Fig. 1. Flowchart of the investigated bioenergy plant.

ecotoxicity (FEP), human toxicity (HTP), photochemical oxidant formation (POFP), particulate matter formation (PMFP), terrestrial acidification (TAP), and water depletion (WD).

In the case of GWP, emissions of carbon monoxide, carbon dioxide, and methane due to the combustion of wood biomass were accounted for as biogenic (i.e., carbon neutral) using a characterization factor equal to zero according to standard LCA procedures. In addition, to evaluate the climate impact of biomass-derived CO_2 emissions, the GWP was also calculated by using a GWP_{bio} factor of 0.25 based on a rotation time of 60 years (Cherubini et al., 2011).

3. Results

3.1. Life cycle inventory

During the inventory phase, the bioenergy plant provided the authors with specific information and data regarding the construction and operation of the plant. Local emissions due to wood and methane combustion were calculated from EPA (2016) and EEA (2016).

Table 1 shows the inventory of main input and output flows and emissions referred to the bioenergy plant on an annual basis. Direct emissions of carbon monoxide, carbon dioxide and methane include both the fossil and biogenic contributions due to the combustion of methane and wood-biomass in the bioenergy plant.

3.2. Environmental performance indicators

Table 2 shows the contribution of the bioenergy plant to selected impact categories. All indicators are referred to 1 kWh of delivered exergy (FU) and to the total annual bioenergy production. In terms of climate impact, when considering CO_2 emissions from wood combustion as biogenic (i.e., carbon neutral), the contribution to GWP resulted in $2.51 \cdot 10^{-1}$ kg CO_2-eq FU^{-1}. Instead, the use of a GWP_{bio} characterization factor of 0.25 led to a value of the GWP of 4.39 10^{-1} kg CO_2-eq FU^{-1}. This alternative way of considering the climate impact of CO_2 emissions from wood biomass determines an increase of 76% of the GWP.

Table 1
Life cycle inventory of the investigated bioenergy plant.

Flow	Unit	Amount
Main inputs		
Wood chips	kg yr^{-1}	7.86E+06
Methane	$m^3 yr^{-1}$	1.30E+06
Transport	t km yr^{-1}	1.57E+05
Electricity	kWh yr^{-1}	4.07E+05
Dust collector	Item(s) yr^{-1}	6.67E-02
Furnace, wood chips	Item(s) yr^{-1}	1.50E-01
Furnace, methane	Item(s) yr^{-1}	1.33E-01
Heat and power co-generation unit	Item(s) yr^{-1}	5.00E-02
Heat and power co-generation unit, ORC	Item(s) yr^{-1}	5.00E-02
Gravel	kg yr^{-1}	1.05E+04
Concrete	m^3 yr^{-1}	3.63E+01
Reinforcing steel	kg yr^{-1}	1.57E+03
Rock wool	kg yr^{-1}	6.50E-01
Alkyd paint	kg yr^{-1}	3.39E+01
Outputs		
Heat	kWh yr^{-1}	3.06E+07
Electricity	kWh yr^{-1}	1.09E+07
Main emissions		
Carbon dioxide	kg yr^{-1}	1.54E+07
Carbon monoxide	kg yr^{-1}	1.43E+04
Methane	kg yr^{-1}	1.04E+03
Nitrogen oxides	kg yr^{-1}	1.55E+04
Sulphur oxides	kg yr^{-1}	1.50E+03
Particulate Matter (PM10)	kg yr^{-1}	2.13E+04
Particulate Matter (PM2.5)	kg yr^{-1}	1.83E+04

Table 2
Contribution of the bioenergy plant to selected impact categories referred to the FU (1 kWh of delivered exergy) and the total annual bioenergy production.

Impact category	Unit	Value
GWP	kg CO_2-eq FU^{-1}	2.51E-01
FD	kg oil-eq FU^{-1}	8.95E-02
FEP	kg 1,4-DCB-eq FU^{-1}	2.87E-03
HTP	kg 1,4-DCB-eq FU^{-1}	3.71E-02
POFP	kg NMVOC FU^{-1}	1.54E-03
PMFP	kg PM10-eq FU^{-1}	2.71E-03
TAP	kg SO_2-eq FU^{-1}	1.08E-03
WD	m^3 FU^{-1}	2.44E-01
GWP	kg CO_2-eq yr^{-1}	4.29E+06
FD	kg oil-eq yr^{-1}	1.53E+06
FEP	kg 1,4-DCB-eq yr^{-1}	4.90E+04
HTP	kg 1,4-DCB-eq yr^{-1}	3.71E-02
POFP	kg NMVOC yr^{-1}	2.64E+04
PMFP	kg PM10-eq yr^{-1}	4.63E+04
TAP	kg SO_2-eq yr^{-1}	1.85E+04
WD	m^3 yr^{-1}	4.16E+06

The HTP was $3.71 \cdot 10^{-2}$ kg 1,4-DCB-eq FU^{-1}. In terms of resources consumption, the FD resulted was $8.95 \cdot 10^{-2}$ kg oil-eq FU^{-1}, while the WD was $2.44 \cdot 10^{-1}$ m^3 FU^{-1}.

The total annual contribution to GWP was $4.29 \cdot 10^6$ kg CO_2-eq yr^{-1}, while the FD was $1.53 \cdot 10^6$ kg oil-eq yr^{-1}. Although these extensive indicators (related to the total annual production of the bioenergy plant) do not allow the comparisons with other technologies, they are still useful since they provide a measure of the overall material and energy demand and impacts due to the annual bioenergy production.

Finally, to facilitate the comparability of the results with other studies, LCA indicators were also calculated per energy unit of heat and electricity separately by using an allocation procedure based on the exergy value of the two outputs (Table 3).

4. Discussion

In this study, a wood-based bioenergy plant located in Northern Italy was investigated by using LCA to calculate indicators of environmental performance.

Selected indicators calculated for the investigated bioenergy plant were compared to the values characterizing fossil-fuels power plants, chosen from the *Ecoinvent* database (i.e., electricity production from natural gas at conventional power plant in Italy, electricity production from oil in Italy, and electricity production from hard coal in Italy). All the indicators calculated for the bioenergy plant were lower than those characterizing fossil fuels-based power plants (Fig. 2). In particular, the amount of CO_2-eq released by the bioenergy plant (0.25 $kgCO_2$-eq kWh^{-1}, Table 3) was lower than the CO_2-eq release characterizing fossil fuels-based power plants, ranking from 0.71 $kgCO_2$-eq kWh^{-1} for a natural gas-based plant to 1.10 $kgCO_2$-eq kWh^{-1} for a hard coal-based power plant. Similarly, the FD calculated for the bioenergy plant (0.09 kg

Table 3
LCA indicators calculated per energy unit of heat and electricity.

Impact category	Unit	Electricity	Heat
GWP	kg CO_2-eq kWh^{-1}	2.50E-01	5.10E-02
FD	kg oil-eq kWh^{-1}	8.93E-02	1.82E-02
FEP	kg 1,4-DCB-eq kWh^{-1}	2.86E-03	5.82E-04
HTP	kg 1,4-DCB-eq kWh^{-1}	2.16E-09	4.41E-10
POFP	kg NMVOC kWh^{-1}	1.54E-03	3.14E-04
PMFP	kg PM10-eq kWh^{-1}	2.70E-03	5.50E-04
TAP	kg SO_2-eq kWh^{-1}	1.08E-03	2.20E-04
WD	m^3 kWh^{-1}	2.43E-01	4.95E-02

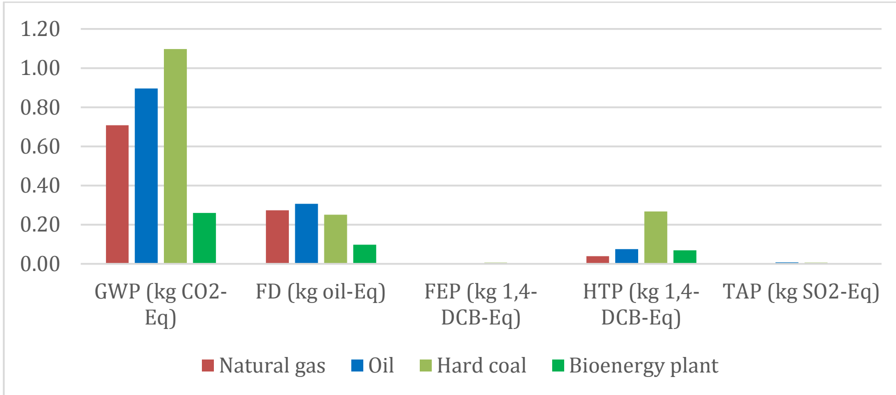

Fig. 2. Contribution of the bioenergy and fossil-based power plants to selected impact categories(indicators referred to 1 kWh of electricity).

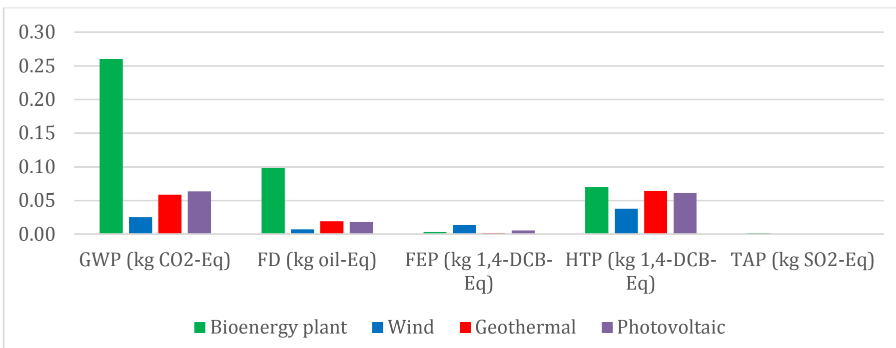

Fig. 3. Contribution of the bioenergy and other power plants based on renewables to selected impact categories (indicators referred to 1 kWh of electricity).

oil-eq kWh^{-1}, Table 3) was lower than the values characterizing fossil fuels-based power plants (Fig. 2).

Moreover, the indicators calculated for the bioenergy plant were also compared to the values characterizing power plants based on renewable resources, selected from the *Ecoinvent* database (i.e., electricity production from wind, 1–3 MW turbine, in Italy, electricity production from geothermal heat in Italy, and electricity production by 570kWp open ground photovoltaic in Italy) (Fig. 3). In this case, while the contribution of the bioenergy plant to some impact categories as FEP was lower than other renewable technologies, the GWP and FD were higher (Fig. 3). The worse environmental performance showed by GWP and FD indicators was mainly due to methane still in use in the bioenergy plant to cover peak loads. Indeed, 84% of the GWP was due to the use of methane (Fig. 4).

These findings show that the environmental impacts of the bioenergy plant could be reduced by replacing methane with additional wood-biomass.

A scenario analysis in which only wood biomass is used to power the bioenergy plant was implemented (Table 4). In addition, the same LCA indicators were calculated per energy unit of heat and electricity (Table 5). The impact indicators in Tables 4 and 5 show that the use of wood biomass instead of methane improves the environmental performance of the bioenergy plant, thus confirming the potential benefits achieved when replacing fossil fuels with wood biomass for bioenergy production.

The findings of this study can support the advancement in the bioenergy field by assessing the potential upscale of this bioenergy option at regional and national level. Such an assessment should

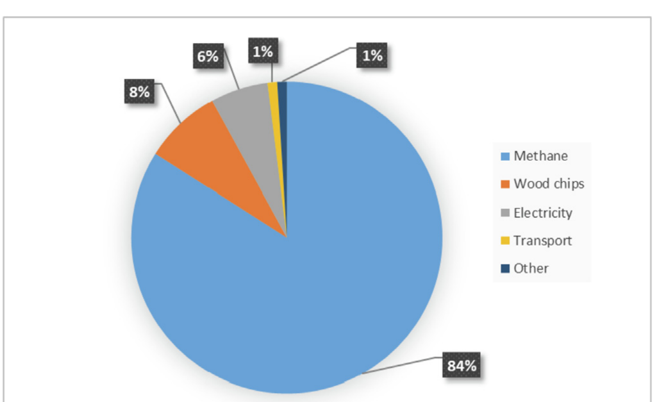

Fig. 4. Contribution of the main input flows to GWP.

Table 4
Scenario analysis: LCA indicators calculated by assuming only wood biomass consumption and referred to the FU of 1 kWh of delivered exergy.

Impact category	Unit	Value
GWP	kg CO_2-eq	7.26E-02
FD	kg oil-eq	1.89E-02
FEP	kg 1,4-DCB-eq	3.38E-03
HTP	kg 1,4-DCB-eq	3.58E-02
POFP	kg NMVOC	1.59E-03
PMFP	kg PM10-eq	3.65E-03
TAP	kg SO_2-eq	8.81E-04
WD	m^3	1.70E-01

Table 5
Scenario analysis: LCA indicators calculated by assuming only wood biomass consumption and calculated per energy unit of heat and electricity.

Impact category	Unit	Electricity	Heat
GWP	kg CO_2-eq kWh^{-1}	7.26E-02	1.48E-02
FD	kg oil-eq kWh^{-1}	1.89E-02	3.86E-03
FEP	kg 1,4-DCB-eq kWh^{-1}	3.38E-03	6.88E-04
HTP	kg 1,4-DCB-eq kWh^{-1}	3.58E-02	7.30E-03
POFP	kg NMVOC kWh^{-1}	1.59E-03	3.24E-04
PMFP	kg PM10-eq kWh^{-1}	3.65E-03	7.45E-04
TAP	kg SO_2-eq kWh^{-1}	8.81E-04	1.80E-04
WD	m^3 kWh^{-1}	1.70E-01	3.46E-02

also consider the availability of wood residues (from forestry and industrial sector) and possible operational constraints at larger spatial scales.

In addition to environmental aspects, there are also socio-economic and ecological aspects to be considered when assessing the benefits deriving from the use of wood biomass for bioenergy production. The economic cost of wood biomass depends on many factors, such as local availability, type, quality, transportation and processing options. In some cases, wood may be more expensive than conventional fossil fuels. In addition, wood biomass competition for alternative needs (e.g., paper and wood industry) can also increase its price.

Moreover, although bioenergy supply chains have the potential to create new job opportunities, income, and other economic benefits for rural communities, public knowledge and awareness of bioenergy are lower than those of other renewable sources such as solar and wind energy. Indeed, in some contexts, the social acceptance of intensive biomass use for bioenergy production is still controversial (Fytili and Zabaniotou, 2017).

For these reasons, also in the case of the investigated bioenergy plant, the LCA methodology could be usefully integrated with socio-economic analysis aimed at assessing the viability of replacing fossil fuels with wood biomass, also taking into consideration the local socio-economic context in which the bioenergy plant is embedded.

5. Conclusions

Wood-based bioenergy production is a timely topic of wide interest. It can represent a suitable energy option particularly in mountain areas characterized by large forest cover and wood biomass availability, and low population density and related energy demand.

The planning and management of bioenergy technologies should be based on the assessment of environmental, ecological, and socio-economic aspects. In this study, the LCA methodology was used to assess the environmental performance of a wood-based bioenergy plant located in an Alpine area of Northern Italy.

The results showed that the use of local wood biomass from forestry and wood industry is an interesting option for replacing fossil fuels consumption while recycling wood residues to support bioenergy production.

The findings of this study can support local managers and policy makers committed to plan and implement renewable energy strategies and circular economy patterns. In addition, they can be useful to assess the potential upscale of this bioenergy option at regional and national level considering the availability of wood residues (from forestry and industrial sector) while verifying possible operational constraints at larger scales.

Finally, since bioenergy is a complex issue involving technological, environmental, and socio-economic aspects, future studies could integrate LCA with other methods exploring the economic profitability and the social desirability of bioenergy production.

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